

# Lightweight Wearable Power Energized by Pentagon's Prize Program

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*The format and general style of this article are somewhat of a departure from the standard articles we publish. Rather, it is more of a "conversation" with principals in the DoD engaged in the pursuit of lightweight wearable power technologies for the warfighter. We hope you'll find it as informative as we did! - Editor*

The sophisticated electronic devices and sensors that give our dismounted warriors an edge on the battlefield also make them prodigious consumers of energy. Helmet-mounted displays, night-vision devices, image intensifiers, satellite radios, computers, laser range finders, global positioning systems, robots, and autonomous vehicles – all these technologies are straining the ability of ground combat personnel to carry adequate power sources to operate them. "Right now, one of the more significant limitations for our ground operations is available power," says Alan Shaffer, Acting Director of Defense Research and Engineering (DDR&E). "Assuming a warfighter has strength to carry a finite amount of weight, we want that weight to be as focused as much as possible on combat power." The question is how to supply enough power that is safe, long-lasting, and lightweight enough for soldiers, Marines, special forces, and Airmen on the ground to carry in a vest or pack along with their other provisions and equipment for extended ground missions. "The issue of wearable power is a very tough problem," says the Army Research Laboratory's (ARL) Senior Program Manager John Hopkins. "You don't necessarily see power on the battlefield. Because it's an enabling technology, and not an end item, it might not be the first problem you think of."

The demand for power will only grow as military technologies evolve, so the Department of Defense (DoD) decided to use its new prize authority, granted by the John Warner National Defense Authorization Act for Fiscal Year 2007, to solicit novel

**"One of the more significant limitations for our ground operations is available power"**

solutions for wearable power systems from the broadest possible population of inventors. By opening up this complex science

and technology (S&T) challenge to nontraditional sources of innovation, the DoD sought not only to advance the concept of wearable power, but also to reach deeper into the well of American ingenuity and create public and academic interest in mission-critical problems facing the US warfighter.

## Wearable Power is a Weight Problem

The DoD estimates that a typical dismounted warrior on a four-day mission carries between 20 and 50 pounds of batteries and rechargers. Combined with the food, water, ammunition, and

equipment needed for a multi-day mission, warfighters may have to carry as much as 150 pounds on their backs. "That's a lot of weight, and we are adding new electronic equipment to their loads all the time," Mr. Shaffer notes. The DoD estimates that, in 10 years, dismounted warriors will need about 50 watts of power per person to operate their equipment. Clearly, the systems used to deliver that power will have to get lighter. "In terms of weight, we were looking to decrease the soldier-carried power component of overall load from the 20 to 50 pound range to a range of less than 10 to 25 pounds. That makes a huge difference for ground combat personnel going out on long-duration missions," says Mr. Shaffer. "We knew we were seeking a tremendous advance in capability."

## Wearable Power is a Logistical and Tactical Problem

The energy and power dilemma came to the forefront in the early days of Operation Iraqi Freedom, when an emergency program had to be instituted to replenish the supply of batteries available to forward operating forces. "The second largest demand for airlift at the time was for batteries," says Mr. Shaffer. US troops needed more battery power than had been planned to operate their equipment. Troops in the southern region used up more than half of the total projected battery supplies available in the first few days of the operation, draining forward stocks and bringing total Army inventory down to dangerously low levels. Troops in the northern region were unable to obtain batteries, which prompted the emergency airlift and triggered around-the-clock production of new inventories to catch up with warfighter demand.

Recognizing that DoD's investment in energy and power was not keeping up with battlefield technology, DDR&E created the Energy and Power Technology Initiative (EPTI) to marshal the full engagement of all the service branches to address these issues across the DoD. The EPTI, chaired by Acting DDR&E Alan Shaffer, brought together senior officials from the Office of the Secretary of Defense (OSD) and the research and development (R&D) organizations of the Army, Air Force, Navy, and Marine Corps. Through a series of technical directions, the EPTI is drawing what is essentially a technology roadmap that encompasses all the services and leverages and coordinates their combined research and engineering capabilities in energy and power.

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### Attention Innovators: Calling All Ideas

After the DoD was accorded prize program authority in late 2006, the Hon. John J. Young, Jr., Undersecretary of Defense for Acquisition, Technology, and Logistics, asked the EPTI to propose an energy and power topic. “In light of the energy issues facing the country in general, and the fact that all three services faced similar challenges, this was clearly a high-priority issue,” according to Dr. John Pellegrino, Director of Sensors and Electron Devices at ARL and the Army’s Principal Representative to the EPTI. Deliberations identified a topic that was pertinent to all the services and would benefit from the participation of a broader community of innovators than those typically engaged in formal defense acquisition programs. Wearable power eventually rose to the top.

In 2007, DDR&E launched the Wearable Power Prize (WPP) program, the first-ever tri-service prize R&D competition. One million dollars was promised to the individual or team that could build a wearable power system that could produce, under realistic operational scenarios, an average of 20 watts of power for more than 4 days (96 hours) and weigh less than 4 kilograms (<8.8 pounds). The key metric for wearable power systems is *energy density* (a measure of available voltage per unit weight). As an additional hurdle, the systems were required to run two voltages (14 and 28 volts) simultaneously without a switch. This technical challenge recognized that different devices require different power draws, thus addressing a power management aspect of wearable power. For the second and third place entries, the WPP competition offered additional prizes of \$500,000 and \$250,000, respectively.

A total of 169 teams registered their prototypes in the competition. Among the initial registrants, self-identified individual private investors far exceeded the number of corporate-affiliated teams, an early outcome that supported one of the WPP’s primary objectives. The entries ran the gamut from enhanced lithium-ion batteries to fuel cell/battery systems, engine/turbine and various other battery hybrids, and a plasma photon system. There were also a variety of fuel types and mixes, including everything from methanol and ethanol, to gasoline, propane, and butane. The competitors were just as diverse: teams hailed from 37 states and included members from several foreign countries. One team that made it all the way to the final competition consisted of two college students from the University of Maine. Other teams represented private companies or were cooperative groups consisting of university professors, students, and small entrepreneurs. Ultimately, 20 teams came to the capstone event, held from 22 September to 4 October 2008, at the Marine Corps Air Ground Combat Center at Twenty-nine Palms, California. A third of those teams were new to working with the DoD, another indication that the prize program was effectively drawing on nontraditional sources of ingenuity. By the time the winners of the “Power Wear Off” were announced on the last day of the competition, the WPP had brought forth prototype wearable power systems that represented the highest energy densities seen to date and more than a twofold decrease in conventional power system weight.

### Why a Prize Program?

“The prize program format for solving a technical problem is a wonderful asset in our toolbox for building DoD’s research and

development portfolio,” says Dr. Pellegrino. Prize challenges are employed by a number of public and private organizations to coax inventors to step forward with new approaches for solving stubborn technical problems. Prize programs are most fruitful “in areas where there is a general concentration of work and an overlap of interest with the private sector,” according to Dr. Edward Shaffer, Associate Director in ARL’s Sensors and Electron Devices Directorate. Prize programs can also function as “hooks for outliers such as university professors who may not be engaged with the defense research community through regular channels,” adds Dr. Shaffer.

One such prize program was the Defense Advanced Research Projects Agency’s Urban Challenge. The program offered prize money to developers of autonomous ground vehicles capable of maneuvering in a mock city environment and executing simulated military supply missions, while merging into moving traffic, navigating traffic circles, negotiating busy intersections, and avoiding obstacles. Another example is the Virgin Earth Challenge under which Richard Branson and Al Gore are offering a prize of \$25 million to anyone who can demonstrate a commercially viable system for removing greenhouse gases from the atmosphere.

A hallmark of a prize program is the likelihood of dual-use applications. In the WPP’s case, this involves solutions that are not only relevant to defense and national security but also have potential for public sector or commercial uses. Wearable power has several dual-use applications. For example, outdoor recreation enthusiasts are interested in small, lightweight, power sources for camping, hiking, fishing, and mountain climbing. First responders, such as police and firefighters, also have technology that depends on a reliable source of lightweight power.

### Wearable Power a Tri-Service Priority

From the start, DDR&E devoted senior-level talent to prize program planning and execution. Dr. William Rees, Under Secretary of Defense for Laboratories and Basic Sciences, assumed executive oversight, while execution responsibility was assigned to the ARL. Senior Program Manager John Hopkins was tapped as WPP Program Manager, and Karen Burrows was named Program Manager for DDR&E. Senior members of the EPTI formed the core executive committee for the WPP competition. They, in turn, pulled in the right subject matter experts (scientists and engineers from each of the service’s R&D organizations) to serve on task-specific teams responsible for execution, safety evaluation, testing, and adjudication. “With respect to defining the criteria for the WPP challenge, the EPTI was well-suited to the task because of the relationships among S&T executives that were already well-established,” says ARL’s Dr. Ed Shaffer. These ties were instrumental in representing the needs and interests of dismounted ground combat personnel in all three service branches. “The predominant customer for wearable power is the soldier,” notes Hopkins. However, by the nature of their jobs, Marines and other dismounted warfighters rely on stealth, sensory, and other advanced technologies in the performance of their critical missions. “We are very concerned about the

“The prize program format for solving a technical problem is a wonderful asset in ... DoD’s research and development portfolio”



weight that a Marine or Navy special forces fighter has to carry,” says Dr. John Pazik, Director of Ship Systems and Engineering in the Office of Naval Research (ONR). These skilled warfighters are “not battery carriers,” continues Pazik, “and we don’t want to burden them with extra weight to power their devices. We want them to do their primary mission, get out safely, and return home. That’s our primary goal.”

“The Air Force has a strong stake with the other services in lightweight, energy-dense wearable power systems,” asserts Dr. Richard T. Fingers, Chief of the Energy Power Thermal Division at the Air Force Research Laboratory (AFRL) at Wright-Patterson Air Force Base. Airmen on the ground support the Air Force mission and work with other dismounted warfighters in theater to complete extremely complex missions. “In our special-purpose research area at AFRL, we have been investigating both wearable power and small unmanned aerial vehicles, which have similar lightweight power requirements,” adds Dr. Fingers. “The prize competition was a true tri-service executed program,” notes Air Force Major Derek Lincoln. Major Lincoln was among the military members of the core execution team who brought onboard the all-important user’s perspective.

### Let the Competition Begin!

After the initial WPP solicitation and a public information forum in September 2007, prospective competitors were given a month-long registration period to signal their intent to compete. To attract a diverse group of nontraditional competitors and remove perceived barriers to prospective entrants, anyone meeting the eligibility requirements could register. Team leaders had to be individual US citizens (although citizenship was not required for team members), at least 21 years old (age 18 for team members), and not currently employed by the federal government, either civilian or military. US and foreign-owned companies were permitted to enter, provided their team leader met the age and citizenship requirements, and state and local government organizations and public universities were also eligible. When registration ended on November 30, 2007, 169 teams had signed up to compete for the WPP purse. There were about ten months remaining before the final competition in the high desert of southern California’s Mojave Desert.

### Getting Down to Work

Setting the technical requirements for the WPP program was a balancing act. The prize criteria had to encourage broad inclusiveness and yet be challenging enough to yield meaningful advances in wearable power technology. “The criteria were the product of a great deal of interaction among technical experts looking at what is possible in the laboratory, what is possible in theory, and what is possible from a practical perspective, particularly with respect to safety and packaging issues,” says Dr. Pellegrino. “We tried to set the bar high enough that clearing it would mean the competitor had done something significant, but not so high that no one could realistically meet it,” he explains.

The execution team drew up a set of rules that reflected the agreed-upon WPP criteria. “It was important for us to make the rules very clear, objective, and definitive. They reflected a reasonable degree of difficulty, and we worked with all the entrants to make sure they had enough information to meet the safety and design criteria,” says Mr. Hopkins. In planning and executing the

WPP competition, the slogan “safety first” had a literal meaning. The safety evaluation team was “top-notch,” says Dr. Pellegrino, comprising about a dozen members from the Army, Navy, and Air Force laboratories in all areas of power generation, including electrochemical (batteries and fuel cells) and conventional engine systems. One of the safety evaluation team’s early tasks was to publish a list of acceptable and unacceptable reactants. Registrants were required to submit a fuel plan, or list of chemicals they planned to use, and a system design. Each of the entries was then evaluated for completeness of required technical data and safety. “The whole premise of the competition was to make the lightest-weight system that met the energy density criteria, and safety features necessarily add weight. So we knew that competitors might compromise safety by trimming system components or taking shortcuts,” says Dr. Terrill Atwater, Senior Research Chemical Engineer in the Communications-Electronics Research, Development, and Engineering Center (CERDEC) at Fort Monmouth.

“One of the safety evaluation team’s greatest concerns at the outset was the unconventional groups that don’t normally do business with the government. Though virtually all the competitors were professional and technically savvy, they might not place the same emphasis on safety that we do in the DoD,” says Dr. Atwater. “We also realized that some competitors might try to pull an idea out of the drawer that had previously been discarded for safety reasons.” As the competitors developed and tested their systems, and the WPP safety evaluation and execution teams continued to interact with them regarding technical and safety issues, the number of entrants began to dwindle. Some teams realized their systems would fall short of the competition metrics, while others ran out of money or did not have the wherewithal to keep going. In other cases, they concluded that their proposed technologies needed more time and effort to mature before practical application would be possible.

Without exception, however, the entrants were technical pioneers seeking to open up new territory with their imaginations. “One of the beauties about America is that we have an incredible wealth of innovative people,” remarks Mr. Shaffer. “Every idea that was presented reflected a different approach, from high-energy density batteries to hybrid fuel cells.”

“One of the beauties about America is that we have an incredible wealth of innovative people”

### Competing Concepts Go Head-to-Head in the Desert

As the capstone event drew near, DDR&E expected 48 teams that had met all the data submission requirements to show up at the Marine Air Ground Combat Center. Lead test engineer Todd Browning, an employee of ARL contractor Alion Science and Technology, was given responsibility for setting up the bench and field tests that would determine the winner. “We had to be prepared to test an unknown number of systems and measure every competing system equally and simultaneously,” recalls Browning. To do that, he arrived at the test site three weeks early to commence building the engineering test operations. It was an exciting opportunity, Browning says, but one that was highly demanding and sometimes challenged his own endurance. “I was there in the desert for 36 days, between the setup and the event itself, and sometimes the temperature went close to 120 degrees.” Browning



**Rayovac Team inflates a boat during final field tests.**

and his team had a critical role in the competition, according to DDR&E Program Manager Karen Burrows. "There was no opportunity for a do-over. We could not have any slip-ups in testing, and it was necessary that we treat every system with the utmost care and respect it deserved." The testing team prepared enough capacity for 40 systems in an initial 92-hour bench test that simulated loads up to 200 watts and was capable of measuring two voltage channels for each system. "After we set up everything, we ran the full 92-hour bench test several times to make sure no test equipment would fail. We also designed special field test monitors that would attach to the vests, allowing the systems to move among the field test stations. We went through every test channel, calibrated it, ran sample tests, and then recalibrated all the equipment," says Browning.

The bench tests were to be followed by nine field test stations that would draw on the finalist systems' remaining power to run equipment with varying power draws. According to ARL's Hopkins, the following battlefield equipment was chosen for the field test phase:

- Heated clothing
- Land warrior system (an ensemble of equipment integrated into a system worn by soldiers and containing a helmet-mounted display, computer communications equipment, GPS, and a host of other battlefield technologies)
- Man-portable radio
- Oxygen-deficient chamber
- Personal cooling garment
- Laptop computer
- Portable ventilator
- Water purification system
- Inflatable boat

The first day onsite at Twenty-nine Palms, only 20 teams showed up, rendering excess testing capacity. As a result, WPP officials offered bench testing for "nonprize-eligible" second systems, as well as field testing for systems that had not achieved the required metrics during the bench test, but still had power left to tackle the gauntlet of nine tasks, allowing these competitors to collect additional data. "I was greatly impressed by the caliber of the bench and field testing," says Jack Taylor, Associate Director



**DuPont/Smart Fuel Cell system powers computer laptop during final tests.**

for Land and Sea Systems in DDR&E and a member of the adjudication team. "The execution team was a highly capable and motivated set of individuals, many with PhDs, and representing all of our military departments." During the testing operations, the adjudication team monitored things closely. "We reviewed the competition's progress on a daily basis, checking the appropriateness of the testing processes and the adequacy of data and analyses. We also validated the final outcomes," says Taylor. "It was quite a feat in terms of manpower, equipment, and environmental conditions," Browning comments.

### The "Lightest and Brightest"

At the conclusion of the field test phase, five teams had fulfilled all competition metrics, after 96 hours of power draw, making them eligible to receive one of the money prizes. To determine the three actual winners, it all came down to fractions of weight:

Ranking	System	Weight (kg)	Prize
1	DuPont/Smart Fuel Cell (SFC) M-25 system	3.762	1st
2	AMI system (Adaptive Materials Inc.)	3.790	2nd
3	Jenny 600S (Capital Connections) system	3.865	3rd
4	Ultralife system	3.989	
5	Ultra Cell system	3.990	

Three more teams demonstrated energy densities in excess of the 480 watt hours per kilogram minimum energy density goal but were deemed ineligible when their systems did not meet all of the competition metrics for 96 full hours of operation. The incredibly low weights of these three systems, though, caught everyone's attention:

System	Weight (kg)
Rayovac system	3.428
AMI second-entry system	3.076
Lockheed Martin system	2.397

The four top finishers were all variants of fuel cell systems, led by DuPont/SFC's fuel cell-methanol hybrid. According to team leader Dennis Kountz, DuPont evolved its trademarked Nafion® material for the component membrane electrode assembly. "We fine-tuned the material in order to build a fuel cell stack that was as efficient a power source as possible. Our partner's advanced technology allowed our system to handle the challenging power draws, voltage requirements, and environmental conditions. After all the testing, we ended up with a fully charged battery and excess methanol fuel."

Rayovac's entry was a lightweight lithium-carbon monofluoride (Li/CFx) battery, the company's most powerful battery pack to date. Although it did not win a prize, its weight and power outputs were impressive. "The Rayovac team basically made a conventional battery that demonstrated a several-fold increase in energy density," notes Mr. Shaffer. "Our goal was to identify promising battery designs that can be further developed into something that is fieldable on a soldier and is safe," says Rayovac team leader Greg Davidson. "The energy density and power control requirements eliminated other types of batteries from the competition, allowing us to show off a little bit more."

These developments, Mr. Shaffer believes, will be showing up in technology solutions that will not only transition to the warfighter but also help solve the critical energy and power issues facing America. "If we can spur the commercial market through these types of competitive activities, that's a great thing," he says.





**Ultralife Team breaks after successful completion of field tests.**

### The Merits of a Competition

Ideally, a prize competition fosters both the levels of entrepreneurialism and the collaboration needed to spur scientific discovery and engineering development. By all accounts, the WPP competition provided fertile

ground for information sharing and data collection. "It was a very good networking opportunity," says Scott Schoeffel, leader for the fourth-place Ultralife team. Out of Navy special operations for less than a year, Mr. Schoeffel knows firsthand how power needs can affect mission success. "I was able to speak with most of the fuel cell researchers who were competing. There was a lot of information sharing about some pretty intriguing ideas, although no one divulged anything proprietary," Schoeffel adds.

All the teams that entered the WPP competition "will have a better perspective on the type of functionality needed in the battlefield environment as a result of their participation and can go on to continue pursuing lightweight, portable power solutions," notes ONR's Dr. Pazik. The sophisticated testing regime provided finalists with extraordinarily useful data for future R&D efforts. "These were complex tests done in the kind of conditions that the competitors probably would not have had the opportunity to replicate themselves," says Mr. Hopkins. "We moved the laboratory out into the desert, and the type and accuracy of the data we collected, and the extreme environmental conditions in which they were collected, has never been done before with respect to wearable power systems," Hopkins continues.

The interactivity that is one of the hallmarks of the prize program format provided another benefit to the WPP participants: access to DoD. Competitors worked with tri-service experts throughout the competition, and those who came to the final event also mingled with many DoD senior officials and acquisition officers. Ultralife's Scott Schoeffel notes, for instance, that he had the chance to speak personally with DoD Undersecretary John Young for almost an hour during the capstone event. "The key for us is that we reached out to folks who were able to make some startling advances in power sources and management technologies," Mr. Shaffer says.

### Redeeming DoD's Investment

According to Dr. Pellegrino, the EPTI and the individual R&D organizations in each service branch are culling through the data with an eye toward following up on the most promising wearable power technologies demonstrated during the competition. Some of these technologies are already known to the DoD, and variants

are being funded through mechanisms such as the Program Executive Office (PEO) structure. Other approaches are in various stages of R&D.

"In that sense, the competition validated our investments in this area," says Dr. Pellegrino. "We found that we have a robust awareness across the DoD power and energy community of many of the approaches, techniques, and materials that were demonstrated. That tells us we are well-connected with the R&D community and have been investing in the right areas."

"Surfacing novel approaches from the competition entails diving into the metrics and identifying matches with our own goals for where wearable power technologies should be three to five years from now," says Dr. Ed Shaffer. In any technology competition, he says, ideas will surface that are not solidly grounded in science and engineering. In other cases, people will try some seemingly odd ideas that may turn out to have a substantial payoff. "By diving down into the data, we may pinpoint materials or approaches that were not presented as a whole system but could offer us some options for future exploration."

One private inventor who showed up at the capstone event is investigating electrostatic power generation (boot power) and has been invited to brief his ideas to ARL researchers. Nevertheless, "Nothing emerged from way out in left field, but there were some interesting twists to the technologies that were brought forth," remarks Dr. Pellegrino.

### INSPIRING NEW INNOVATORS

Informing the public and the broader scientific and entrepreneurial communities about wearable power was yet another positive outcome. "The prize program was successful in enticing both users and developers to broaden their thinking about the power outputs that are possible in a small package and the range of areas in which these technologies are applicable," says Dr. Pellegrino.

The WPP competition was also successful in an area that it did not initially set out to exploit. The DoD S&T enterprise needs to replenish its ranks of scientists and engineers with new talent. By their exposure to DoD technical experts throughout the competition, many of the younger competitors were introduced to the defense research community as a prospective employer that offers some of the best technical challenges that exist today.

Also mindful that a better informed public includes future generations of scientists and engineers, Karen Burrows masterminded a "Kid's Day" on October 3, the day between the end of the bench test and the culminating field test. "This special event helped inspire young students to consider careers in defense research and engineering," says Burrows.

Major Lincoln agreed to lead the 4-hour event that brought some 300 kids from three local schools to the Marine Air Ground Combat Center for an educational outreach event dubbed "The Future Charges Up Here." Among other activities, senior engineers led groups of students on tours of the competition area and the Technology Showcase tent, where they were able to see and



**Rayovac Team member demonstrates system operation in prone position.**

even touch some of the latest technologies being transitioned to the warfighter. “It is important to perk up kids’ interest now so that, when they make choices in school, these technologies will stick in their minds as something cool that they could be a part of,” says Major Lincoln. “Kids’ Day was a huge hit.”

#### “OUTSTANDING”

“This was a competition in the truest sense of the word. We set clear, objective metrics and took great pains to make sure every competitor got the same experience, whether they were a single individual or a large corporation. That was something we worked very, very hard to achieve,” says ARL’s Hopkins.

Although one would expect the first-place team to be pleased with the competition, DuPont/SFC team leader Dennis Kountz also understands the enormity of the effort. “We were impressed with how DoD ran the competition because we thought they were biting off a huge task. They did an outstanding job.”



**DuPont/Smart Fuel Cell M-25 Team with \$1M award.**

“The results exceeded our expectations on many fronts,” says DDR&E’s Burrows. “We wanted this inaugural prize competition to raise the public’s interest and increase their engagement in this critical technology area, and we did that.”

Adds Dr. Rees, “The real winners from this competition are our ground warfighters. The wearable power systems demonstrated at the competition show great promise for dramatically reducing

the weight of the power systems they must carry while performing their critical missions.”

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All photos by Larry Shank, US Army Research Laboratory.

#### NOTE

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